# IN-SERVICE TESTING OF TEMPORARY GROUNDING JUMPER ASSEMBLIES USING TIME DOMAIN REFLECTOMETRY

By


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ABSTRACT

# In-Service Testing of Temporary Grounding Jumper Assemblies Using Time Domain Reflectometry

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The electrical utility industry relies on safety procedures and equipment to protect linepersons from the hazards associated with high voltages. The current standards and test methods for protective jumper assemblies are disjointed and largely implemented in an ad hoc fashion. This thesis reviews the current state of the art and the standards and practices currently in place. Models, analyses and an investigation of testing methods are used to propose a comprehensive test plan and new test fixtures to provide accurate and traceable results. These results will allow the electrical utilities to insure that the protective jumper assemblies are in fact providing the protection needed by their workers.

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# INTRODUCTION

## Motivation

The United States Department of Labor reported approximately 20 lost time accidents for electrical utility workers in 2004.(US Department of Labor 2006) This same agency reports, on average, 21 fatalities per year for the same class of workers for the years 1992 through 2002. (US Department of Labor 2006) While the statistics were not detailed enough to indicate which accidents were related to the use of temporary jumpers, there are data that support that utility line workers are at significant risk. (Stout 1998) During the period from November 1982 to December 1994, The National Institute for Occupational Safety and Health (NIOSH) investigated 224 electrocution incidents which resulted in 244 occupational fatalities.(Stout 1998) These investigations were conducted as part of the Fatality Assessment and Control Evaluation (FACE) program of NIOSH. Although utility line workers typically receive extensive training in electrical safety and have access to the necessary personal protective equipment (PPE) required to deal with the hazards associated with electrical energy, they had the highest number of fatal injuries. Twenty-six utility line worker fatalities were the result of failure to utilize required personal protective equipment (gloves, sleeves, mats, blankets, etc.). One hundred forty seven incidents were reported involving voltages above 600 volts. Of these incidents, 111 involved distribution voltages (7,200-13,800 volts) and 21 incidents involved transmission voltages (above 13,800 volts). Electric power line workers were victims in 47 of the incidents involving transmission and distribution voltages.(Stout 1998)

Every lineperson that climbs a pole, rides up in a bucket, or supports others from the ground recognizes that they are about to encounter voltages and currents that can radically alter, and even take, their life in the blink of an eye. These workers rely on procedures, tools and equipment to mitigate the risks associated with working on overhead transmission and distribution lines. The existing standards, procedures and recommendations for the testing of key components of equipment in this industry are largely speculative and difficult to substantiate or rationalize.

**Physiology**

The human body responds to electrical stimulus in a variety of ways depending on the type and amount of energy imposed on the subject. The body's response to 60Hz alternating current at low current levels, 0.7 – 1.1 milli-amps (mA) typically produces a tingling sensation. Between 6 and 9 mA the sensation becomes uncomfortable to painful. Approximately 16 mA of current is considered the 'let go' threshold at which the subject is unable to release his grip as a result of the simultaneous stimulation of the flexor and extensor muscles in the arm.(Stout 1998) Since flexor muscles are more powerful than the extensor muscles, the grip is maintained as long as the stimulus is present. Generally speaking, exposure to a current of 100mA for 3 seconds can cause ventricular fibrillation and 2.75 A for only 0.03 seconds usually insures death in a 70 kg (154 lb.) subject.(Dalziel 1956) It is important to note the stimulus leading to death has components of both time and energy.

**Focus**

This research is focused on four main areas. The first being the review and understanding of the existing standards governing temporary grounding jumpers on high voltage transmission and distribution lines. The next focus area is on the existing testing methods and data that are available. As with all forms of testing the goal is to craft the test such that it provides a view into how the unit under test will perform under its normal conditions of use. However, all too often the conditions of use are extreme, and therefore testing becomes difficult. For example, to actually test a $CO_2$ fire extinguisher under conditions of use, the chemical charge is expended and the extinguisher is no longer fully effective. Similarly, how are meaningful test data obtained for a protective jumper that is potentially going to be exposed to tens of thousands of amps at tens of thousands of volts? Or, how is field testing just prior to use possible? Thirdly, the research focuses on an alternative method of testing these jumpers using Time Domain Reflectometry (TDR). Finally to insure the safety and longevity of the workers, the protective equipment (i.e. temporary grounding jumpers) must guarantee that the amount of electrical current the worker would be exposed to is well below dangerous levels. Several factors contribute to successfully protecting workers in these situations. These are:

1) The equipment needs to work reliably.
2) Procedures need to be developed for using the equipment.
3) The equipment and procedures need to be easy to use.

This remainder of this thesis contains six major chapters. They are: a discussion of the literature, including standards and data (Chapters 2 and 3). Next a discussion of the existing test methods and the background required to understand these methods (Chapter 4). Thirdly, a discussion of how TDR might be used to provide more accurate non-destructive test data (Chapter 5). A discussion of the test results and methods follows (Chapters 6 and 7). Lastly, recommendations and conclusions are provided (Chapter 8).

*Chapter 2*

# CURRENT STATE OF THE ART

## Introduction

This chapter discusses the literature review and relevant contributions of this literature. Next, the effects of electric current on the human body are examined and how voltage, current, resistance, time and environmental factors affect the human response to electric shock. A simplified electrical model of the worker caught in a fault situation is presented along with a detailed look that the electrical resistance of the human body. Finally, an overview of the component parts of a grounding jumper and their physical and electrical characteristics is presented.

## Literature Review

This literature review was done primarily for three reasons:

1. To bring focus to the research project.
2. To help form the basis of the research.
3. To help guide the direction of the research.

There are two main components of the research that require further examination. The first being the concept of providing adequate grounding of high voltage conductors, and the second being the testing of cables used for that purpose. [Because there is no single source of information that melds these two topics the literature reviewed focuses on one of these two main areas.]

**The IEEE Guide for Safety in Substation Grounding (IEEE 2000)** provides information on grounding procedures, the effects of shock on the human body and the definitions of many components involved in an electrocution scenario. The guide discusses the basic problem and the conditions of danger when a worker is exposed to potentially lethal voltages. The guide suggests that a range of tolerable current exists for the human body and this range is dependent on several factors. The effects of frequency, magnitude and duration are discussed with formulas presented for each effect. The guide also references Dalziel's (Dalziel 1956) work with electric shock effects on animals. The concept of 'let-go' current, or the amount of current a subject can receive and still 'let go' is discussed as well as the fibrillation threshold. It is pointed out that Dalziel's initial work defined the current flowing through the human body, $I_{B,}$ for a 50 kg subject as:

$$I_B = \frac{0.116}{\sqrt{t_s}} \qquad (1)$$

Where $t_s$ is defined as the duration of the exposure in seconds. In this vein the guide presents additional data suggesting that other researchers have concluded different values for $I_B$. Ferris (1971) suggests 100 mA as the fibrillation threshold based on experimental data. Additional research suggests the threshold varies depending on whether the duration of the shock is longer or shorter than a literal heartbeat. Because fibrillation current is a function of body weight the constant, 0.116, has to be adjusted. Further studies by Dalziel (Dalziel 1956) suggest the constant rises to 0.157 for a 70 kg subject. Biegelmeier's Z curve is discussed as another alternative for calculating fibrillation current based on the exposure time, and the magnitude of the current.(Geddes 1971) The next section of the guide discusses the resistance of the human body and the various paths the electrical current may take. The terms, 'touch voltage', 'metal to metal touch voltage' and 'step voltage' are introduced along with the idea that ground isn't really ground. Under normal conditions the point known as electrical ground is very nearly equal to zero ground potential. That is to say the voltage of the ground at a local point is equal to the voltage of the ground at a remote point. During a fault condition the local ground can experience ground potential rise (GPR) and have a higher voltage than the ground at a remote point. The remaining sections of this guide discuss concepts targeted more towards typical touch situations and grounding solutions for AC substations.

**The Effects of Electric Shock on Man (Dalziel 1956)** is the basis for most of the other literature discussing concepts that pertain to placing a worker in a hazardous situation. Through extensive experimentation of both animals and humans, Dalziel defined the basic ranges of currents and their respective reactions. Additional work by Gieges (Gieiges 1956) in 1956 and Geddes(Geddes 1971) build upon Dalziels' work and suggest alternative calculation methods. Few, if any of these alternative methods stray very far from Dalziels' original findings.

**Worker Deaths by Electrocution (Stout 1998)** and Census of Fatal Occupational Injuries(US Department of Labor 2006) provide the statistical data which are the motivation for this research.

**ASTM Standard F2249 (ASTM 2003)** is the prevailing document on testing temporary grounding jumpers. This standard covers 'the in-service inspection and electrical testing of temporary protective grounding jumper assemblies which have been used by electrical workers in the field.' This standard does not discuss application, care, use and maintenance of these jumpers. F2249 contains four sections on test procedures and one section on cleaning and reconditioning even though it previously claimed no discussion of care, use and maintenance. The first section, Section 5, deals with visual and mechanical inspection prior to testing. The section suggests that jumpers may be taken out of service without electrical testing should they exhibit any of the following physical limitations:

- Cracked or broken ferrules and clamps
- Exposed broken conductor strands
- Cut or badly mashed or flattened cable
- Extensively damaged cable-covering material
- Swollen cable jacket, soft spots or visible corrosion

Section 6 details preparing and measuring the jumper prior to electrical testing. Since the Standard only provides acceptable overall resistance values based on the length of the jumper the length measurement is fairly critical.

Section 7 outlines the types of electrical tests than may be preformed. The Standard does not give pros and cons of the various types nor does it provide a rationale for choosing one over the other. The tests suggested are essentially millivolt drop tests with a fixed forcing current of 10A. The two tests differ in that one is alternating current (AC) with no frequency specified, 60Hz was assumed, and the other being direct current (DC). In both cases the supply is regulated to 5%. The standard states that based on 'ASTM Round Robin Tests' a 5% variance in overall cable resistance is acceptable. Additional 'conservative analysis' suggest that the resistance of the clamp and ferrule assemblies was constant at 0.16 milli-ohm (m**Ω**). This provided an equation for the impedance of the assembly as:

$$Zm = \sqrt{(1.05RL + 2Y)^2 + (XL)^2} \qquad (2)$$

Where R is equal to the resistivity of the cable, m**Ω**/ft, L is the length of the cable, in feet, from ferrule to ferrule, and Y is the resistance of the ends, in m**Ω**, or 0.32 m**Ω** per the standard. X is the reactance of the cable, also in mΩ/ft. For DC testing the reactance term goes to zero. The standard provides several footnotes on the perils of testing with an AC source. The results can be skewed based on the cable geometry, the way it's laid on the floor, the spacing of the endpoints during the test and the effects of nearby metal objects that could alter any mutual inductance coupling that may be occurring. The standard provides no AC test data to support or refute the notes. The standard does provide a table of pass/fail values for jumpers of various sizes, from #2 cable to 4/0 cable, and lengths, from less than 1 foot to 50 ft.

In 1996, the Bonneville Power Administration (BPA), in cooperation with ASTM conducted a series of tests on temporary grounding jumpers. The 2/0 jumpers were subjected to 30 cycles of 26 kA fault current.(Kolcio 2002) A portion of these results were included in F2249-03. These results showed that in 40% of the test cases jumpers that met the criteria of F2249-03 failed under normal conditions of use. In a similar study, commissioned by Ontario Hydro Services Company, the data shows that 75% of the jumpers that met the F2249 criteria failed under similar conditions of use (25 cycles of 22 kA fault current).(Kolcio 2002)

The final Sections of the standard, the X2 sections, discuss a temperature differential test method whereby the jumper was subjected to a 200 A (60Hz RMS +/- 5%) or larger current, based on ASTM F855 Table 5, for 3 minutes. At the end of 3 minutes the current was removed and the cable was scanned with an IR non-contact thermometer. The idea is that hot-spots are bad because the jumper should heat uniformly. The standard suggests temperature differences of 15°F or greater should be investigated but allowances for different sizes and types of clamps and ferrules should be made based on user experience.

Since F2249 only deals with the resistance of the jumper assemblies other information must be available for the proper use of the jumpers for the protection desired.

In **Maintaining Line Worker Safety Through Maintenance and Testing of Grounding Equipment** (King 1998), King discusses the need for testing of equipment but does not suggest any methodology other than what is recommended in ASTM 2249.

**The Calculations of the Temperature Rise and Load Capability of Cable Systems** (Neher 1957), often referred to as the Neher-McGrath Method, this paper provides the mathematical basis for understanding the behavior of the jumper assemblies as they are exposed to fault currents. Essentially what Neher and McGrath show is:

1. The impedance of a cable increases as a function of temperature.
2. The temperature of a cable increases as a function of current flowing in the conductor.
3. The current carrying capacity of a conductor is a heat transfer issue, not an electrical conductivity issue.

Therefore, a temporary grounding jumper that has an impedance of X at room temperature will have increased impedance under fault conditions because of the temperature increase caused by the large fault current. These calculations form the basis for the ampacity tables in Section 3.10 of the National Electric Code.(NFPA 2005)

**Electrical Resistance Data from Fault Tests for 2/0 and 4/0 Temporary Grounding Jumpers** (Kolcio 2002) is a brief overview of the testing issue and a recap of the testing done at Bonneville Power Administration (BPA) and by Ontario Hydro Services Company (OHSC). In essence both BPA and OHSC attempted to correlate jumpers that were deemed good, under the guidelines of ASTM 2249, and jumpers that passed testing under actual conditions of use. The data collected by both entities showed that a significant number of jumper assemblies that met the criteria defined in ASTM 2249 failed under actual conditions of use. It is interesting to note that neither entity added a 1000 Ω resistance in parallel with the jumper under test to observe the current that a subject might experience under fault conditions.

**ASTM F 855-97** (ASTM 1997) discusses the physical characteristics of and guidelines for selecting jumpers, ferrules and clamps. Electrical and mechanical properties as well as workmanship, appearance and finish are all discussed. The standard provides some guidance for obtaining adequate protection equipment for grounding de-energized power lines and equipment.

**IEEE Guide for Protective Grounding of Power Lines** (IEEE 2003). This standard expands the resistance model of the human body presented in IEEE 80 (IEEE 2000) to address variables previously neglected. The new model includes variables for the resistance of the skin, clothing and footwear. The ground potential rise (GPR) is also defined as a function of the fault current and the resistance to remote earth. However, the body resistance is still stated to be 1000 Ω for determining current limits. The standard does indicate that this value is under review with wet vs. dry skin and the body's changing impedance based on voltage being the major factors under consideration. The standard goes on to discuss types of fault currents, their magnitudes and how they might be generated. A graph showing the magnitude of the fault current declining as the distance from the station or source increases is provided. Automatic reclosure considerations presented directly parallel those in IEEE 80. Induction and capacitive coupling between adjacent circuits on a double circuit line are discussed as potential sources for fault current and a range of values are presented. Section 5 of the Standard suggests the makeup of the grounding set and directly calls upon ASTM 855 for guidance. Section 6 discusses path impedance, positioning, derating, re-use and worksite vs.

bracket grounding issues. Sections 8, 9 and 10 are almost cookbook like instructions for what, where and how to ground distribution and transmission lines. Section 11 begins to parallel ASTM 2249 as it discusses physical inspection of the jumper assemblies. From there it deviates in suggesting a milli-volt testing method using a 25 A DC source. ASTM 2249 suggests a 10 A DC source. (ASTM 2003) A brief discussion of high current testing is provided and the standard ends with a section on ground electrodes and suggested uses.

**Additional literature** was reviewed as part of this research. Some of this additional literature was found to have one of two items of interest and is cited in the bibliography. Most of the additional relevant literature referred to either ASTM 2249, Dalziel's work or Neher-McGrath.

**Summary**

In summary, the current state of the art focuses on low current DC testing to insure a low resistance jumper. The existing research agrees the resistance of the human body is modeled as 1000 $\Omega$ and that the maximum current a worker should be subjected to under any fault conditions is 100 mA. Although the current findings acknowledge fibrillation current is time dependant, body resistance is voltage dependent and jumper resistance is current dependent, the testing methodologies remain static in nature apparently relying on conservative estimates to compensate for the variability of the components.

*Chapter 3*

# MODELING

**Overview**

To discover an effective method for using temporary jumpers to protect workers it was necessary to determine how to electrically model those workers and the situations to which they may be exposed. Dalziel (Dalziel 1956), Geddes (Geddes 1971), and Gieiges (Gieiges 1956) did a great deal of work on the response of the human body to electric current. The IEEE developed a standard based on this work that quantifies the electrical properties of the human body. For DC and low frequency AC currents, below 100Hz, the human body is essentially resistive. The value of this resistance varies based on a large number of factors. Once the behavior of the body and the behavior of the jumper have been defined, the simplest model for protection can be shown. For the jumper to protect the worker the jumper must pass enough current to keep the voltage potential across the worker, $V_{man}$, from reaching a potential high enough to generate harmful levels of current flowing through the body, $I_{man}$. As illustrated in Figure 3.1, $I_{man}$ must be less than an established safe threshold for as long as necessary for the circuit to be interrupted and the fault current removed.

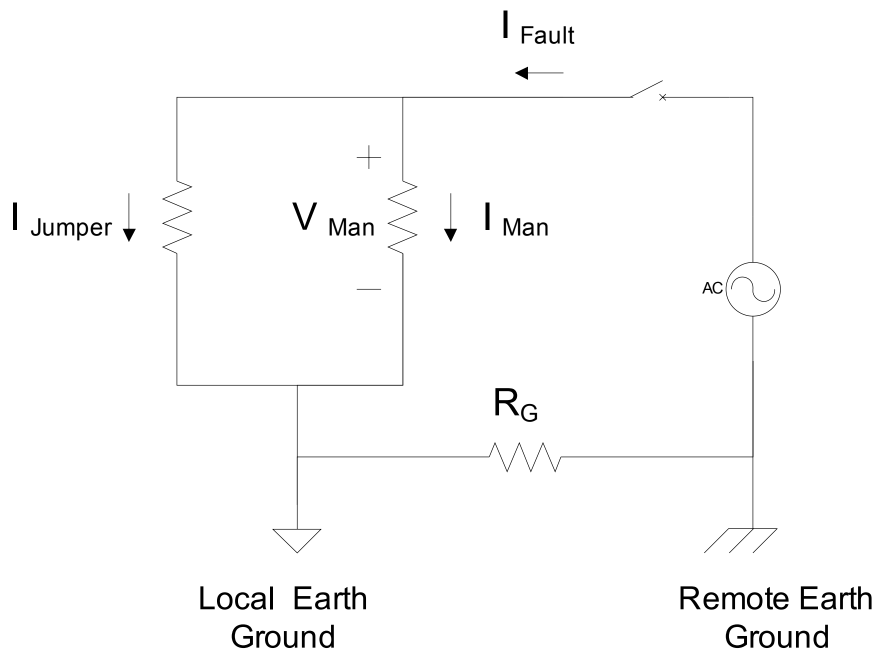


**Figure 3.1 Schematic of Jumper Protection Method**

Each utility is responsible for determining their safety standards. This thesis was not intended to determine what that level is. For discussion of this model the maximum allowable current through the worker was assumed to be 100 mA, the 3-second fibrillation threshold commonly discussed throughout the literature reviewed.(Dalziel 1956; IEEE 2000; IEEE 2003)

## Body Resistance

The human body has two main resistance components, the internal resistance and the resistance of the skin. The internal resistance is constant while the skin resistance is highly variable and dependent on outside factors. (IEEE 2003) Table 3.1 shows a compilation of resistance values observed by Dalziel when forty subjects were tested. (Dalziel 1956)

| | Hand-to-Hand | | Hand-to-Foot |
|---|---|---|---|
| | Dry<br>Ω | Wet<br>Ω | Wet<br>Ω |
| **Maximum** | **13,500** | **1260** | **1950** |
| **Minimum** | **1500** | **610** | **820** |
| **Average** | **4838** | **865** | **1221** |

**Table 3.1 Electrical Resistance of the Human Body (IEEE 2003)**

Additionally, the resistance of the body varies depending on the voltage applied. Data presented by IEEE showed the body resistance asymptotically approaching 1000 $\Omega$ for wet skin and 1500 $\Omega$ for dry skin, as the voltage approaches 500 volts. (IEEE 2003) Clothing, gloves and footwear can also add to the resistance of the body and can be quite substantial. To be conservative, and not rely on these variable items to dictate the results, these additional resistances are ignored in safety assessments. (IEEE 2003) The final component of the resistance calculation is the contact resistance. Contact resistance is defined as the resistance between the point of contact to the live conductor and the return voltage point, or remote ground point. For a subject standing on the ground the contact resistance is a function of the ground resistance between the local ground point and the remote ground point. For a lineman the pole, tower or other structure must be included in the calculation. Ground resistivity can vary from 10 $\Omega$ – m for wet organic soil to as high as 10,000 $\Omega$ – m for bedrock. (IEEE 2003) While the calculation for the actual resistance of the body for a given set of conditions is not overly complex it would rely on a series of assumptions regarding the conditions or a series of measurements of same. For the purposes of determining body current limits the resistance of the worker, $R_{man}$, to 1000 $\Omega$ which is presumed to be a fixed value. (IEEE 2000)

**Jumper Resistance**

Once the body resistance is known, or assumed, it can be shown that the required resistance of the protective jumper, $R_{jumper}$, is dependent on the amount of fault current, $I_{fault}$,, present. $I_{man}$ is then defined as:

$$I_{man} = \frac{R_{jumper}}{R_{man} + R_{jumper}} \times I_{fault} \qquad (3)$$

Figure 3.2 shows the relationship between jumper resistance and fault current to limit the current through the worker to 100 mA.

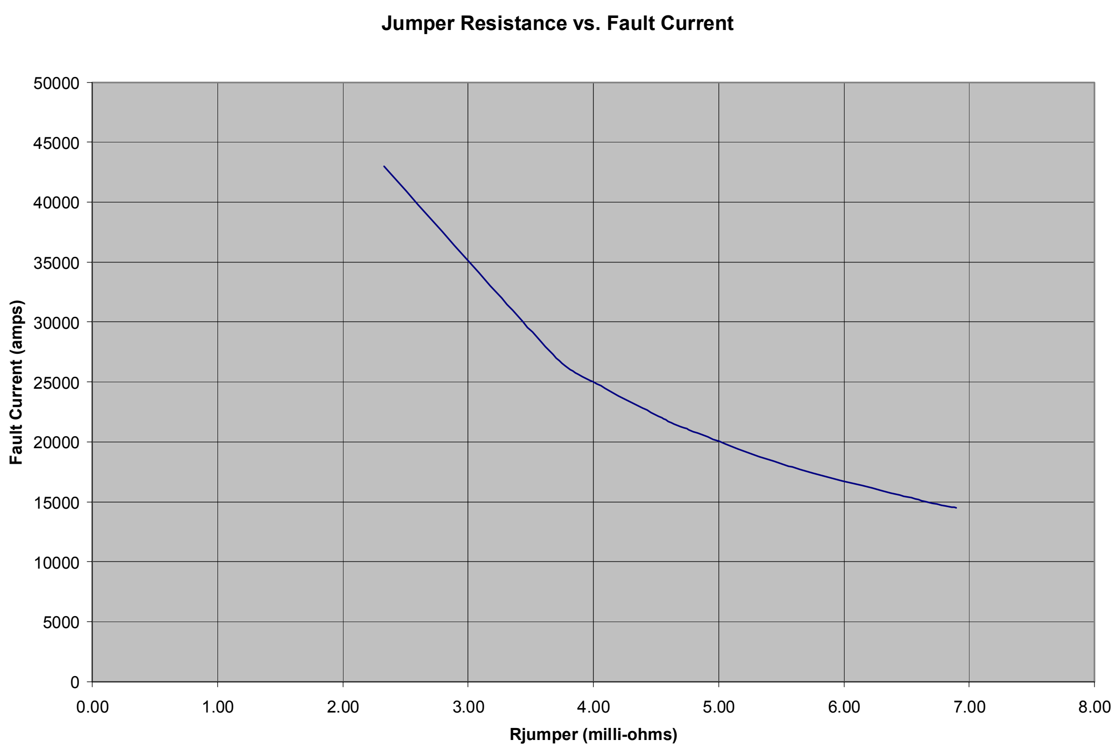


**Figure 3.2 Jumper Resistance vs. Fault Current**

Dalziel, Biegelmeyer and others have shown fibrillation current limits to be a function of the time of exposure and body weight. (Dalziel 1956; Geddes 1971; IEEE 2003) For a 70 kg (154 lb.) subject the relationship between the fibrillation current threshold, $I_B$, and the time of exposure is given by:

$$I_B = \frac{157}{\sqrt{t}} \qquad (4)$$

and is shown in Figure 3.3.

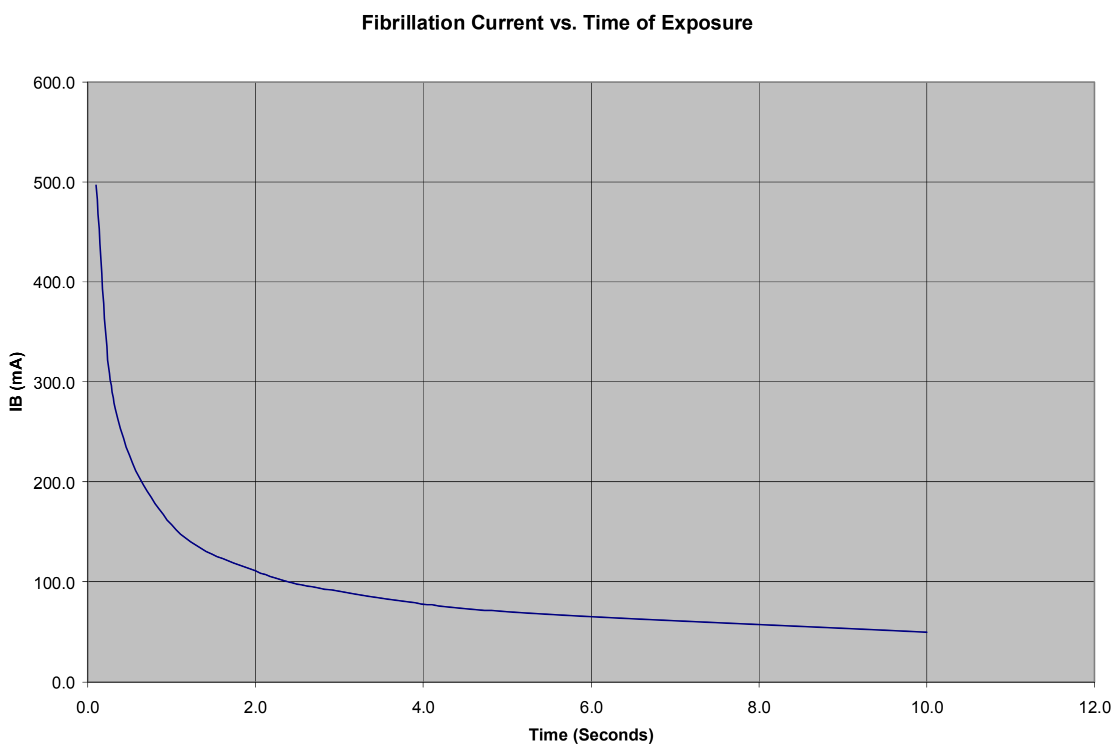


**Figure 3.3 Fibrillation Current Threshold vs. Time of Exposure**

Additionally, the resistance of the jumper is also a function of temperature and that the temperature of the jumper is a function of the energy it is subjected to. For steady state conditions the resistance of the jumper at elevated temperature increases and is given by:

$$R_{T2} = R_{nom}\left[1+\alpha\left(T_2 - T_{nom}\right)\right] \quad \text{(5)(Neher 1957)}$$

Where, $T_2$ is the final temperature, $T_{nom}$ is the nominal temperature for the conductor, typically 75°C, $R_{nom}$ is the resistance at nominal temperature and $\alpha$ is the temperature coefficient of the conductor material. $\alpha_{cu}$ = 0.00323 at 75°C and $\alpha_{al}$ = 0.00330 at 75°C. The relationship in Equation 5 assumes the temperature of the conductor is known. In the case of the jumper, the fault current will elevate the temperature which will increase the resistance which will increase the temperature and so on. Neher-McGrath gives an extremely detailed set of calculations for approximating the ampacity as a result of temperature rise in a cable under steady state conditions. In essence the temperature rise is composed of the temperature rise as a result of its own losses and the temperature drop produced by dielectric loss. Dielectric loss is the heat rejected from the cable based on the thermal insulation properties of the outer coverings of the cable. Neher-McGrath focuses on multiple, insulated conductors in a conduit and spends a significant amount of effort describing the thermal interactions of the conductors. It has proven impractical to manipulate the Neher-McGrath equations to solve for the temperature rise of the cable based on the applied current. An iterative thermal model would be needed to accurately see the resistance change due to the fault current. A simple approach using basic heat transfer equations also quickly breaks down when one considers the path of least thermal resistance is along the cable, through the ends and onto the distribution line. Using some simple assumptions about the heat transfer paths involved it can be shown that the temperature rise in the cable can exceed 300°C during the fault. The melted and burnt insulation reported by Bonneville Power and Ontario Hydro would seem to support this. (ASTM 2003) If the jumper experiences this magnitude of temperature rise, Equation 5 shows an increase in resistance of more than 70%.

For the jumper assembly to provide protection it must be sized appropriately for the maximum fault current possibly to be encountered. Table 3.2 shows the ultimate rating capacity of jumper assemblies using various cable sizes. The tolerable amount of fault current is a function of time. The time dimension appears as reduced fault current as the duration of the fault current increases. The continuous current rating of each conductor is provided for comparison. (ASTM 1997)

| Short Circuit Properties - Symmetrical kA, RMS 60 Hz | | | | | | |
|---|---|---|---|---|---|---|
| | Ultimate Rating/Capacity | | | | | |
| Cable Size | 6 Cycles (100 mS) | 15 Cycles (250 mS) | 30 Cycles (500 mS) | 60 Cycles (1 S) | Continuous Current Rating | Jumper[1] Resistance (mill-ohms) |
| #2 | 28 | 18 | 13 | 9 | 0.20 | 7.69 |
| 1/0 | 47 | 29 | 21 | 14 | 0.25 | 4.76 |
| 2/0 | 59 | 37 | 26 | 18 | 0.30 | 3.85 |
| 3/0 | 74 | 47 | 33 | 23 | 0.35 | 3.03 |
| 4/0 | 94 | 59 | 42 | 29 | 0.40 | 2.38 |
| 250 kcmil | 111 | 70 | 49 | 35 | 0.50 | 2.04 |
| 350 kcmil | 155 | 98 | 69 | 49 | 0.55 | 1.45 |

Notes: 1 - Jumper resistance must include all components (cable, ferrules and clamps). Jumper resistance limits worker exposure current to 100 mA under 30 cycle conditions.

**Table 3.2 Ultimate Current Ratings of Typical Jumper Sizes (ASTM 1997).**

Using the information from Table 3.2 it can be seen that to adequately protect a worker who could be subjected to a 42 kA fault current the protective jumper assemblies must have a total resistance of 2.38 m$\Omega$ or less assuming the circuit protection would interrupt the fault within 30 cycles or ½ of a second. From the tables provided in ASTM F2249, these jumpers should be no more than 35 feet long.(ASTM 2003) There is some disagreement about the appropriate resistance of the cable clamps and connections. ASTM F2249 suggests 0.16 m$\Omega$ per connection while others recommend as much as 1.0 m$\Omega$ per connection.(Chance 1999) In the latter case a jumper cable length of 6.25 feet or greater would violate the safety conditions.

**Clamps, Ferrules and Cables**

Every connection point in a jumper assembly is a potential source of increased resistance. There are six connections in a single jumper:

- Distribution Line to Clamp
- Clamp to Ferrule
- Ferrule to Cable
- Cable to Ferrule
- Ferrule to Clamp
- Clamp to ground bar.

The number of connections for a three phase system can be reduced from eighteen by the use of a multi-cable grounding clamp. There are additional connections possible between the grounding bar and the local ground. Figure 3.4 shows a typical clamp used on a grounding jumper set. Clamps are typically furnished in one of three types according to function and method of installation. (ASTM 1997)

- Type I – For installation on de-energized conductors equipped with installation eyes.
- Type II – For installation on de-energized conductors with permanently mounted hot-sticks.
- Type III – For installation on permanently grounded structures.

Additionally, clamps are provided in two classes according to the type of jaws used for the main contact surface. Class A jaws are smooth for smooth contact surfaces. Class B jaws are serrated and intended to abrade or penetrate corrosion on the surface of the conductor being clamped. (ASTM 1997)

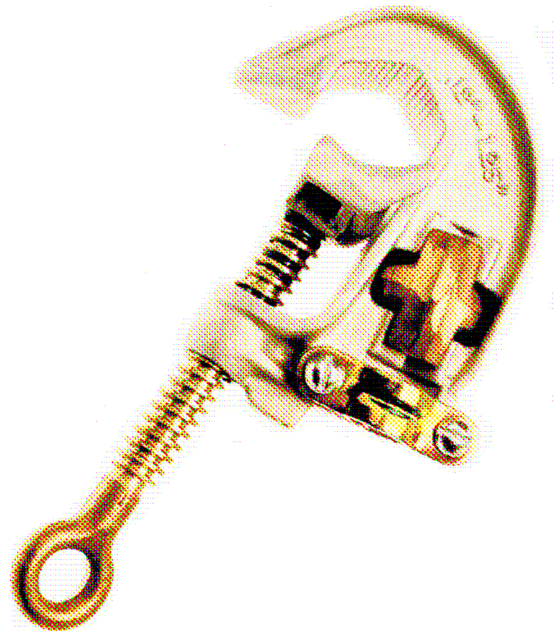

**Figure 3.4 Typical Type I, Class B Clamp Assembly**
(Photo Courtesy of Hubbell Power Systems, Inc.)

Other types of clamps are available and provided for ease of use while maintaining proper physical and electrical properties. Figure 3.5 shows a ball and socket clamp with a ferrule being used to connect a vehicle body. Ferrules are also provided in a range of styles and sizes. Ferrules are intended to insure maximum contact, lowest resistance, between the cable and the clamp. Type III, IV, V, and VI ferrules have inspection or vent holes to aid in the maintenance of the equipment. (ASTM 1997) Protective jumper assemblies like those shown in Figure 3.6 are rated for fault currents defined by Table 3.2. These ratings insure that all components of the assembly, cable, clamp and ferrule, can withstand the ultimate fault current listed. (ASTM 1997)

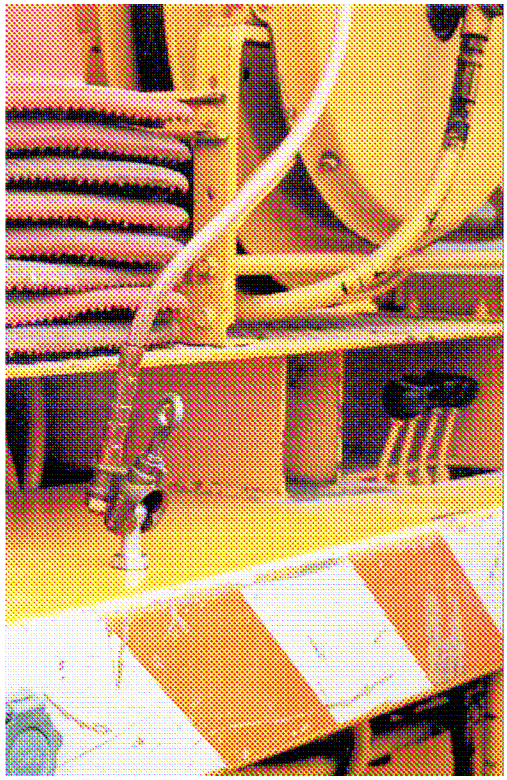

**Figure 3.5  Socket Clamp with Ferrule**
(Photo Courtesy of Hubbell Power Systems, Inc.)

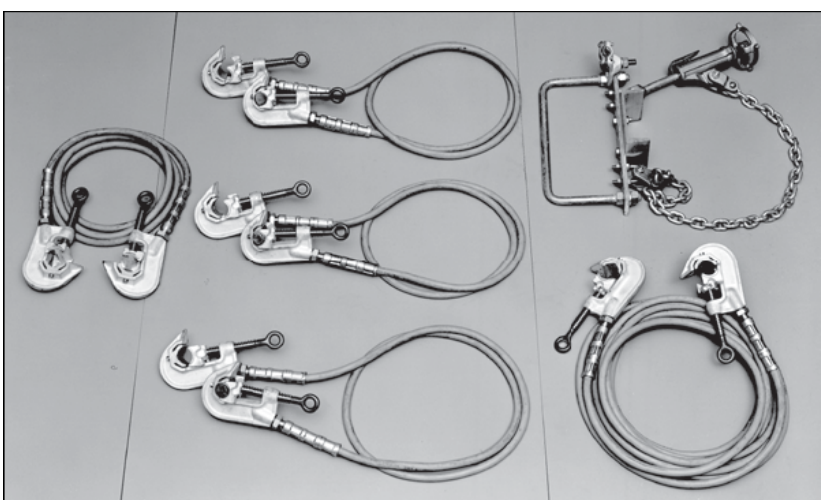

**Figure 3.6  Complete Jumper Assemblies**
(Photo Courtesy of Hubbell Power Systems, Inc.)

**Conclusions**

The components of the fault scenario, jumper resistance, body resistance, clamps, ferrules and ground resistance can be modeled. As with the current state of the art the models are simple and static tending to ignore the time, voltage, and current dependencies present. This simplification allows for the creation of simple and easy to apply test procedures. While a more complex model may provide a more complete prediction of what will happen under fault conditions, it becomes unfeasible to implement in a testing environment.

*Chapter 4*

# MEASUREMENT METHODS

## Introduction

This chapter discusses basic measurement techniques and how they are or might be applied to temporary grounding jumpers.

## Measurement Accuracy

ASTM F2249 provides resistance values for copper grounding jumper assemblies range from 0.039 mΩ to 9.009 mΩ depending on the length and size of the conductors used.(ASTM 2003) Furthermore the standard specifies applying a 10 A direct current to the assembly and measuring the associated voltage drop. Ohms law defines the relationships between voltage, current and resistance as:

$$R = V / I \tag{6}$$

A 50 foot long 4/0 AWG stranded copper cable should have a resistance of approximately 2.893 mΩ. (ASTM 2003) Therefore at 10A the voltage across the resistance should be 10 x 0.002893 or 0.02893 volts, or 28.93 mV. On a typical good quality digital voltmeter, data sheets reviewed for Fluke and Agilent, the maximum resolution is as low as 0.1mv. Now the best result is trimmed to 28.9 mV. Further investigation reveals that for DC voltages the accuracy is 0.3%. The result is now 28.9 mV +/- 0.1 mV. For AC voltage measurement accuracy drops to between 0.4% and 2.0% (Fluke 1995-2006; Technologies 2007) or 28.9 mV +/- 0.6 mV. Agilent also recommends using the NULL function to zero out the thermal effects prior to conducting measurements. (Technologies 2007) The point of this brief discussion is to illustrate how test equipment can inherently introduce a few percentage points of error.

**Test Fixtures**

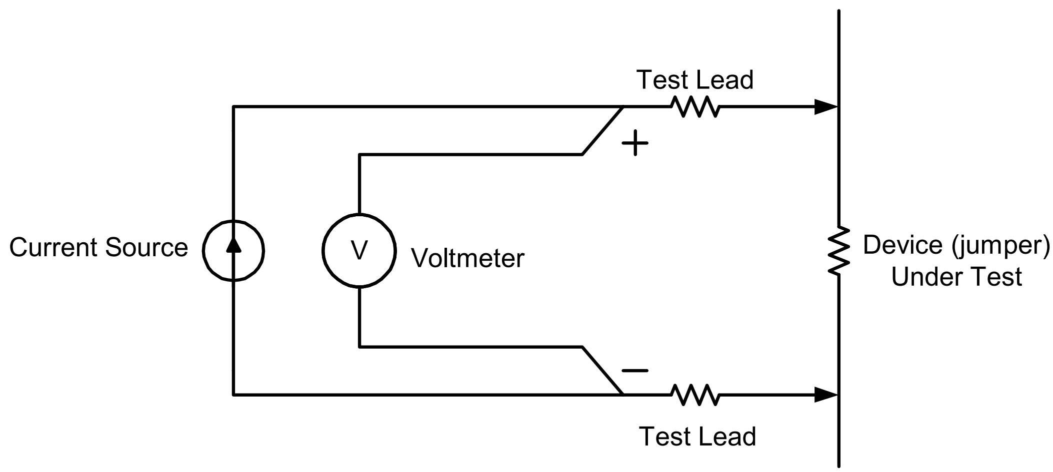


**Figure 4.1 Schematic of Two-Wire Tester**

In a typical two-wire measurement, illustrated by figure 4.1, the current source and voltmeter, voltmeter being defined as any generic voltage measuring apparatus, are co-located in the instrument and only two connections are available. The tester uses a constant current source to generate a voltage across the load being tested. The voltmeter records the voltage, divides by the known current and displays the resistance. The resistance displayed includes the resistance of the test leads and/or test fixture. Normally the very low resistance of these fixtures is not a factor. However in grounding jumper assembly measurements the lead and fixture resistance becomes significant. This fixture resistance is sometimes referred to as a "tare value" that could be removed to meet a specification for maximum resistance of the jumper. While the tare value can be used to adjust measurements, it's not as simple as it first appears. First the accuracy of the tester is reduced by the ratio of fixture to jumper resistance. Adjusted measurement error is defined by:

$$E_{adj} = E_{tester}\left[\frac{R_{fixture} + R_{jumper}}{R_{jumper}}\right] \tag{7}$$

This means that a 2.893 mΩ jumper measurement with 30 mΩ of fixture resistance and a 1% tester accuracy is subject to a 7.9% measurement error.(Systems 2003) Additional variation in resistance comes from the point of contact between the jumper and the fixture. This resistance variation from measurement to measurement can add significantly to a given resistance and will get worse as corrosion, moisture and other factors affect the contact surfaces. Since this variation is dynamic, using a fixed tare value could cause resistance thresholds to be set too high and defective jumpers would be allowed to pass.

**Existing Test Methods**

There are four main test methodologies for testing grounding jumpers. These measurement methods are not unique to grounding jumpers although some of the forcing conditions are specifically called out.(ASTM 2003) The four methodologies are:

- Millivolt Testing
- 10A AC/DC Testing
- Pulse Testing
- Thermal Testing

**Millivolt Testing**

This is the method used by most all electronic multi meters. Essentially a small current is forced into a load and the subsequent voltage reading, usually in millivolts, is converted and displayed to the user. As discussed earlier, most hand-held testers us a two wire approach which reduces accuracy for the sake of convenience and lower cost. Figure 4.2 shows a simplified schematic of a typical 4-wire meter. Again, a current source forces a known current through the 'force' terminals and the device under test. Since the current source is constant the resistance of the 'force' leads is inconsequential. The voltage is then read from the 'sense' terminals..

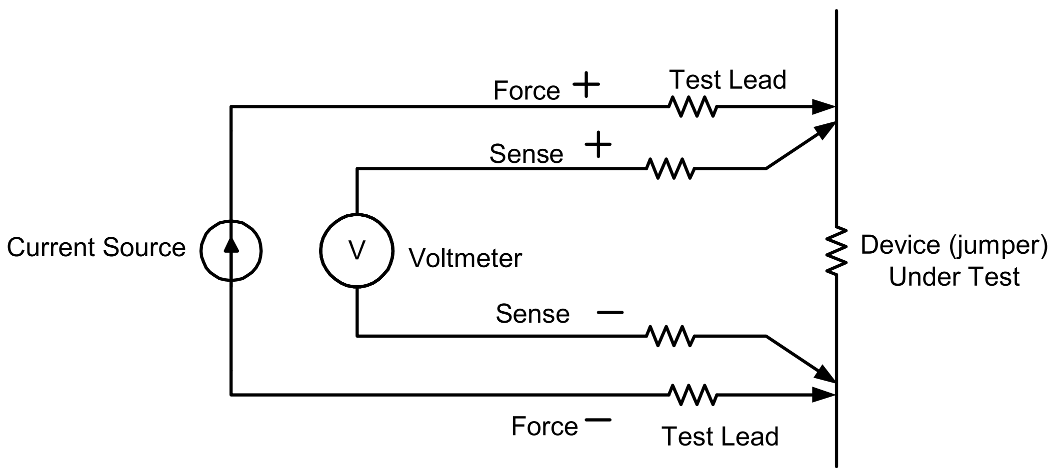


**Figure 4.2 Schematic of a 4-Wire Meter**

Figure 4.3 shows a simplified schematic of the sense circuit used in the four wire meter. $R_m$ is defined as the internal resistance of the meter, $R_{tl1,2}$ are the resistances of the test leads and $R_{dut}$ is the resistance of the device under test.

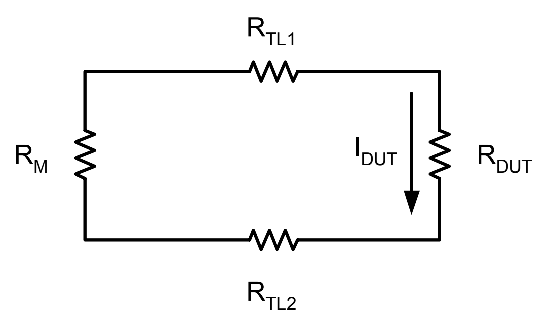


**Figure 4.3 Simplified Model of 4-Wire Sense Circuit**

. Kirchoff's voltage law states the sum of the voltages must equal zero. By convention:

$$0 = V_{DUT} + V_{TL2} - V_M - V_{TL1} \qquad (8)$$

Since I is constant and the test leads should be the same resistance on both positive and negative terminals:

$$V_{TL2} = V_{TL1} \quad \therefore \quad V_M = V_{DUT} \qquad (9)$$

By properly cabling the fixture to a four-wire instrument the error associated with the test leads and fixtures will be cancelled and accurate measurements of the jumper will be obtained.

**10A DC Testing**

Commercially available digital volt meters, both two and four wire, do not typically allow the end user to regulate the forcing current. ASTM 2249 suggests a minimum forcing current of 10A is appropriate for jumper testing. The number 10 appears to be arbitrary but the idea is that a current large enough to break down small amounts of oxidization (high resistance paths) should be used. Though not specifically stated in the standard it is my belief that this is an attempt to overcome the adverse environmental conditions the jumpers may be tested under as well as allowing for the harsh conditions the jumpers are subjected to. The measurement technique should be the same as for millivolt testing. ASTM 2249 gives acceptable jumper resistance values for DC testing only. (ASTM 2003)

**10A AC Testing**

ASTM 2249 also acknowledges a 10A, 60 Hz AC test. Since the jumpers are used primarily on 60 Hz AC transmission and distribution lines it makes sense to test under similar conditions.

When performing AC testing additional conditions apply. The impedance of the cable is a function of the cable and the test electrode spacing. (ASTM 2003) As the segments of the cable approach one another they interact and the reactance component of the cable impedance approaches zero. Additional considerations must be made for the location of the cable during testing. Since this measurement takes into account the reactance of the cable, anything that can affect this reactance (location, proximity to other conductors, electromagnetic fields, etc.) must be avoided or compensated for.

**Pulse Testing**

ASTM 2249 suggests that 10A is the maximum forcing current used to test jumper assemblies to avoid self heating of the cable. Studies have shown the heating of a cable is a function of $I^2t$. Neher-McGrath has shown that as a conductor heats the resistance changes.(Neher 1957) To avoid this problem short duration pulses of current can be injected into the jumper and corresponding voltages can be read to calculate the resistance of the cable. A voltmeter with sample and hold capabilities would be required to capture this information.

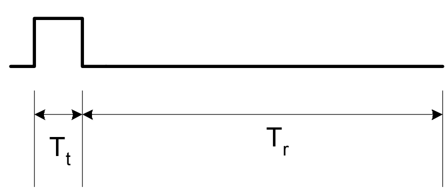


**Figure 4.4 Potential Pulse Sequence**

Figure 4.4 shows one possible sequence of pulses to avoid self heating. The values of Tt, the time the line is energized, and Tr, the time the line is at rest, could be determined empirically for various wire sizes. Ambient conditions would need to be included as well. This method could allow for higher forcing currents to be used if desired. Higher currents more closely resemble actual conditions of use and would be preferred if they could be applied in a nondestructive manner. One commercially available product uses values of 50 and 500 mS for Tt and Tr respectively. (Chance 1999)

**Thermal Testing**

Unlike the previous methods this method encourages cable heating. A significant current, 100 A for example, is applied to a jumper assembly for an extended period of time. Once the forcing current is removed a thermal analysis of the cable is performed. Typically the jumper is scanned with an infra red thermometer. Any significant deviations in the temperature profile may suggest potential problem areas in the jumper.

**Commercial Application**

The most common commercially available jumper test set uses the 10A DC testing method in a portable easy to use device. The unit has a default safety threshold current of 100 mA. This threshold is adjustable by changing a parameter in the device. The parameter adjusted is 'voltage across man' and has a default setting of 100 V. The unit assumes a resistance of 1000 **Ω**. The vendor references Dalziel as the basis of these values. This device also incorporates a variation on pulse testing. The unit energizes the jumper with a 5 VDC source current limited to 10 A long enough to sample the resistance. The unit then waits 500 milli-seconds before testing again. (Chance 1999)

The industrial statistician George Box is credited with the quote 'all models are wrong, some are useful'. In the discussion of testing temporary grounding jumpers this philosophy applies to the available test methods; 'All of the test methods are interesting, none of them are definitive'. Each test method reveals a piece of information about the jumper assembly being tested. However, as the Bonneville Power Administration demonstrated, 30% of jumpers that successfully passed the testing provided for by ASTM 2249, failed under actual conditions of use.(Kolcio 2002) Secondarily, and perhaps more importantly, jumpers that pass all tests including BPA conditions of use may not adequately protect line workers due to misapplication. The use of an 80' long jumper when a 40' jumper would suffice is an example of misapplication. The 80' jumper, even in good working condition, allows twice as much current to flow through the line worker during a fault. Some test equipment manufacturers have taken it upon themselves to interpret life safety research and make their equipment provide results aimed at preventing misuse.(Chance 1999) OSHA is equally vague on personal safety requirements afforded by grounding jumpers. Section 1926.954 states 'Grounding to tower shall be made with a tower clamp capable of conducting the anticipated fault current.'(OSHA 2005) Both IEEE and ASTM provide guidance and suggestions, by way of standards, for what the maximum allowable touch and step voltages workers should be exposed to and still survive. While nobody wants to deal with the loss of life of a worker due to misunderstanding, misapplication or blatant ignorance of standards, there is no regulatory agency providing guidance and enforcement of these standards.

*C h a p t e r 5*

# ALTERNATIVE TESTING METHOD

## Introduction

This chapter will discuss an alternative testing method and the results would be expected if it were applied to the testing of temporary grounding jumpers.

## Overview of Time Domain Reflectometry

Time Domain Reflectometry (TDR) came to the attention of geologists and other scientists in late 1930's. Today there is significant use of TDR to monitor geological and other mechanical motion. A coaxial cable is placed in the ground, and pulses are sent down the cable. When an earthquake or structural fault damages the cable, the readings on monitoring equipment attached to the cable (in this case, an oscilloscope) will change instantly, alerting users to compromised structural integrity. TDR works in a cable the same way radar works in free space. In Figure 5.1 a pulse of energy is transmitted down the cable at $t_0$. When that pulse reaches the end of the cable, $t_e$, or a fault along the cable, part or all of the pulse energy is reflected back to the instrument and arrives at $t_f$. TDR measures the time it takes for the signal to travel down the cable, see the end or fault, and reflect back. TDR then converts this time to distance and displays the information as a waveform and/or distance reading. The accuracy of this distance reading depends upon knowing how fast signals propagate in the particular cable being measured.

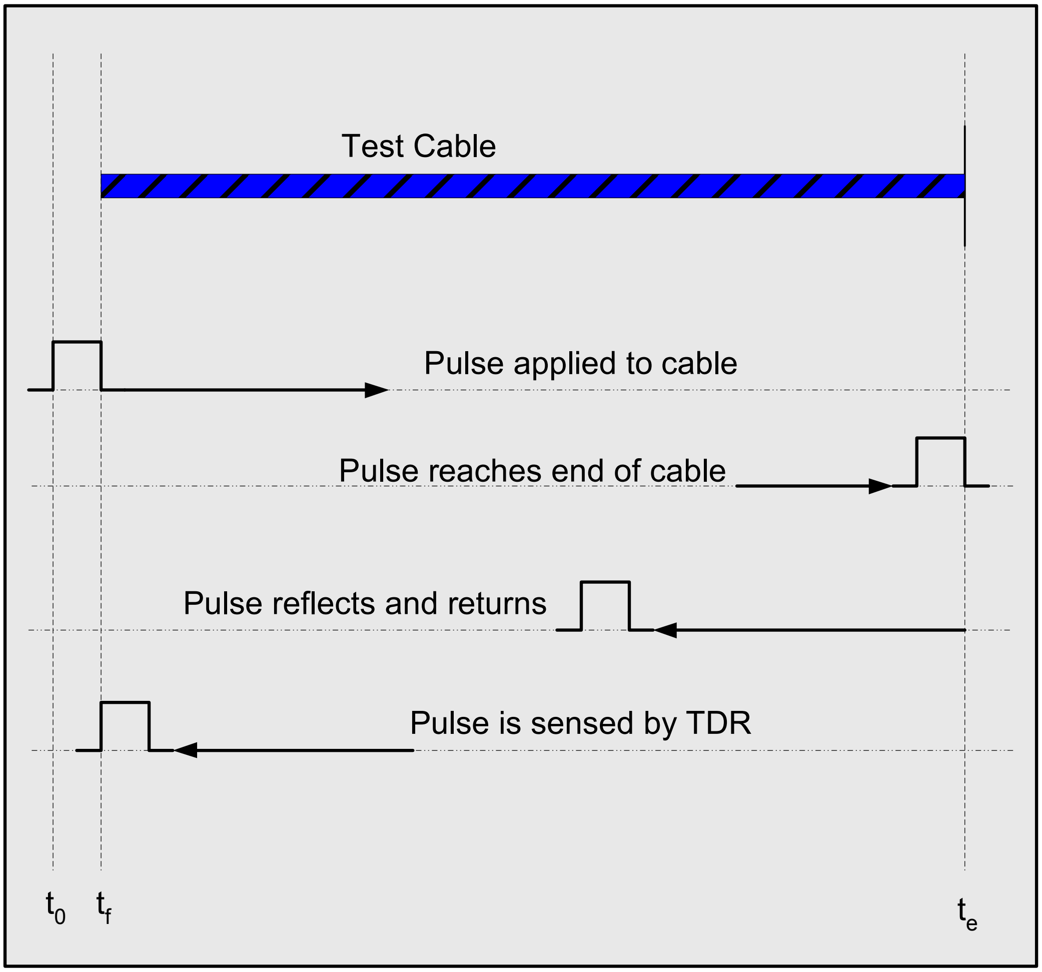


**Figure 5.1 Ideal TDR Operations**

### A Practical Application of TDR

Geologists bury coaxial cable in vertical wells to sense earth movements. Under normal conditions TDR would allow the geologist to 'see' the entire length of cable in the well. If a fault, or shift in the earth, occurred and created a fault in the cable, TDR would tell exactly where, at what depth, the fault occurred.(Infrastructure Technology Institute) Figure 5.2 shows a simplified diagram of this event. What geologists have done is to observe the damage to a cable and relate it to a physical phenomenon. We can apply this same technology to make a determination about the integrity of a temporary grounding jumper assembly.

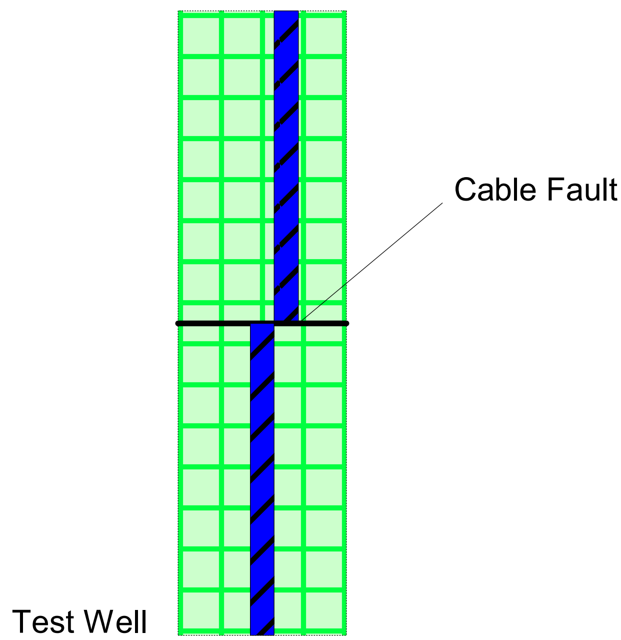


**Figure 5.2 Faulted Cable Example**

**TDR Applied to Jumpers**

The injected pulse radiates down the cable and at the point where the cable ends some portion of the signal pulse is reflected back to the injection point. The amount of the reflected energy is a function of the condition at the end of the cable. If the cable is open condition the energy pulse reflected back is a significant portion of the injected signal with the same polarity as the injected pulse, also shown in Figure 5.1.

If the other end of the cable is shorted to ground or to the return cable, the energy reflected is in the opposite polarity of the injected signal.

If the end of the cable is terminated by a resistance having a value matching the characteristic impedance of the cable, all of the injected energy will be absorbed by the terminating resistor and no reflection will be generated. This is the desired condition for signal antennas.

Any change in the cable impedance due to a connection, major kink or other problem will generate a reflection in addition to the reflection from the end of the cable. By timing the delay between the original pulse and the reflection it is possible to determine the point on the cable where the anomaly exists.

**Velocity of Propagation**

TDR equipment is classed one of two ways. Metallic, which is designed for use on metal conductors, and optical for use with fiber optic cables. A metallic TDR can be used on any metallic conductor. Coaxial cable or telecommunications cables are the most common types tested with TDR. Power cable or temporary grounding jumpers in this case, present some unusual challenges. There are two major issues to be overcome when using a TDR on a power cable. The first is velocity of propagation or VOP. VOP is a parameter that characterizes the speed at which an electrical signal travels through a medium. VOP is typically specified as a percentage of the speed of light in a vacuum which has a VOP of 100. VOP can also be expressed as a function of the dielectric constant '$\varepsilon$' of the cable.

$$VOP = \frac{100}{\sqrt{\varepsilon}} \qquad (10)$$

Communications cables have VOP's in the range of 42 – 70.(Reed 2002). Table 5.1 shows some typical, and not so typical insulation materials and their associated VOP and delay values.(Cable 2003) The correct VOP is essential to accurate calibration of the TDR unit. VOP provides the basis for the overall delay through the cable. Both delay and VOP are needed to calibrate the TDR. When properly calibrated the TDR will give accurate locations of any faults found in the cable.

| Material | ε | VOP | Delay |
|---|---|---|---|
| **Typical Insulation Materials** | | | |
| Cellular TFE | 1.38 | 85% | 1.2 |
| FEP | 2.1 | 69% | 1.47 |
| Silicone Rubber | 3.6-2.1 | 53%-69% | 1.92-1.47 |
| TFE | 2.1 | 69% | 1.47 |
| Polyethylene | 2.3 | 66% | 1.55 |
| PVC | 8.2-3.0 | 35%-58% | 2.9-1.75 |
| Nylon | 45.-3.6 | 47%-53% | 2.16-1.92 |
| **Non-Typical Insulation Materials*** | | | |
| Snow (Fresh) | 1.2 | 91% | 1.1 |
| Vaseline | 2.2 | 68% | 1.49 |
| Beeswax | 2.8 | 60% | 1.69 |
| Ice | 3.2 | 56% | 1.8 |
| Glass | 8.2 | 35% | 2.9 |
| Water (Distilled) | 82 | 11% | 9.2 |
| | | | |
| * Theoretical values | | | |

**Table 5.1 VOP Values of Common Insulation Types**

## Practical Considerations

The second challenge will be in connecting the cable to the TDR. TDR units are designed to handle BNC, RJ-11, RJ-45 and other small connectors. A fixture will be required to allow quick, yet quality connections to be made from the jumper assembly to the TDR. The pulse generated by the TDR takes a certain amount of time, albeit very small, to launch. This time translates into a distance at the beginning of the cable which the TDR cannot 'see'. A properly designed fixture should be able to hide in the TDR blind spot or at least create a known signature on the TDR. While this blind spot is useful at concealing reflections associated with the fixture it suggests that faults in the first few feet of cable or cable to ferrule connection in an actual jumper assembly could go unreported. Procedurally, testing the jumper assembly from both ends should eliminate this concern. Figure 5.3 provides a schematic representation of the test apparatus.

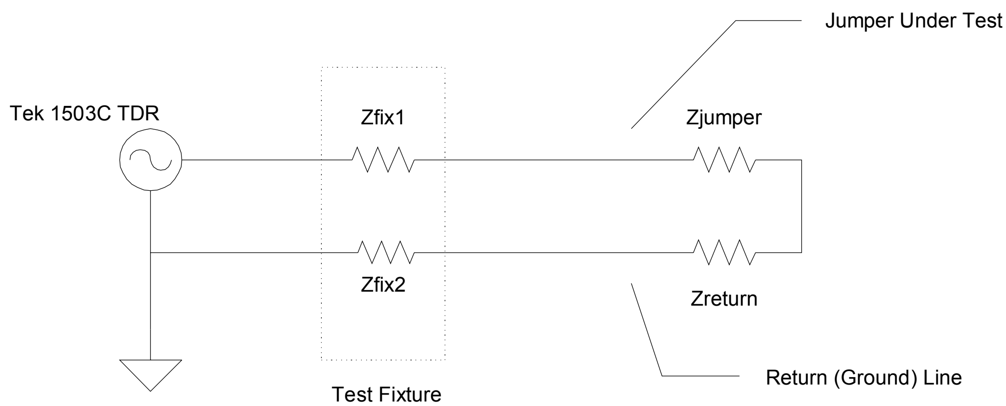


**Figure 5.3 Schematic Representation of the Test Apparatus**

### Expected Results

The TDR equipment to be used is a Tektronix 1503C Metallic TDR Tester. The specifications for the 1503C are given in Appendix A. The Tektronix 1503C outputs pulses which need to be treated like an AC signal. For this reason the fixture and cable impedance must be addressed, not just the resistance. $Z_{fix1,2}$ represent the impedances expected with the test fixture. Zjumper is the impedance of the jumper under test and Zreturn is the impedance of the return line. Figure 5.4 shows the ideal expected results of testing a good jumper with TDR. The test apparatus originally shown in figure 5.3 is overlaid in Figure 5.4 with the TDR pulses and expected reflections.

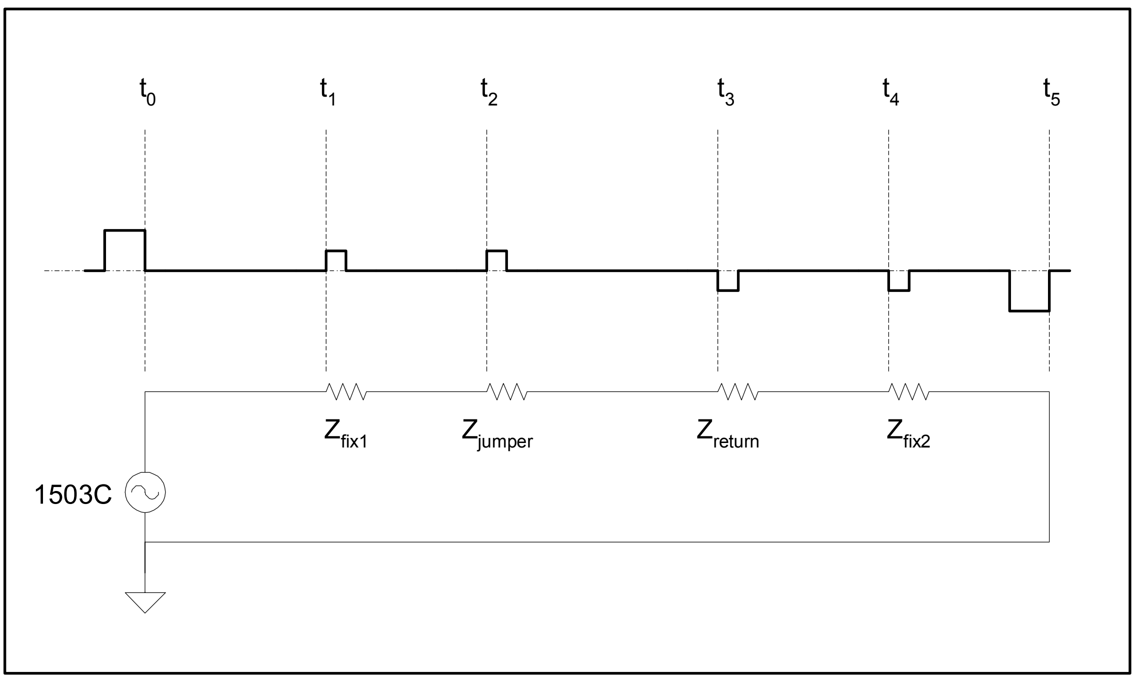


**Figure 5.4 Expected Results**

At each change in impedance a portion of the initial pulse should be reflected back. Since the impedances for the return line and fixture impedance 2 represent common ground their reflections as well as the final reflection are inverted. The values of $t_1 - t_5$ are dependent on the physical characteristics of the fixture and cable lengths of the jumper and return lines. Reflections at $t_1$ and $t_2$ may actually be hidden in the blind spot of the TDR. The actual pulses will not be nice square shapes as shown here rather they will be rounded due to the impedance mismatching between the TDR and the cables being tested. A damaged, open, cable should represent itself with a large positive reflection returning before the final negatively oriented pulse. Ideally one could relate the magnitude of this pulse to the degree of damage to the cable.

*Chapter 6*

# TEST APPARATUS AND RESULTS

## Introduction

This chapter discusses the apparatus used to actually test cables with a Tektronix 1503C Metallic TDR, the specifications of which are given in Appendix B. The test setups and results are also presented here.

## Test Setup

Figure 6.1 shows a test apparatus using simple cable clamp to connect the grounding jumper to the TDR. The PVC conduit provides a channel for supporting the jumpers and assists in keeping them aligned and in close proximity to one another.

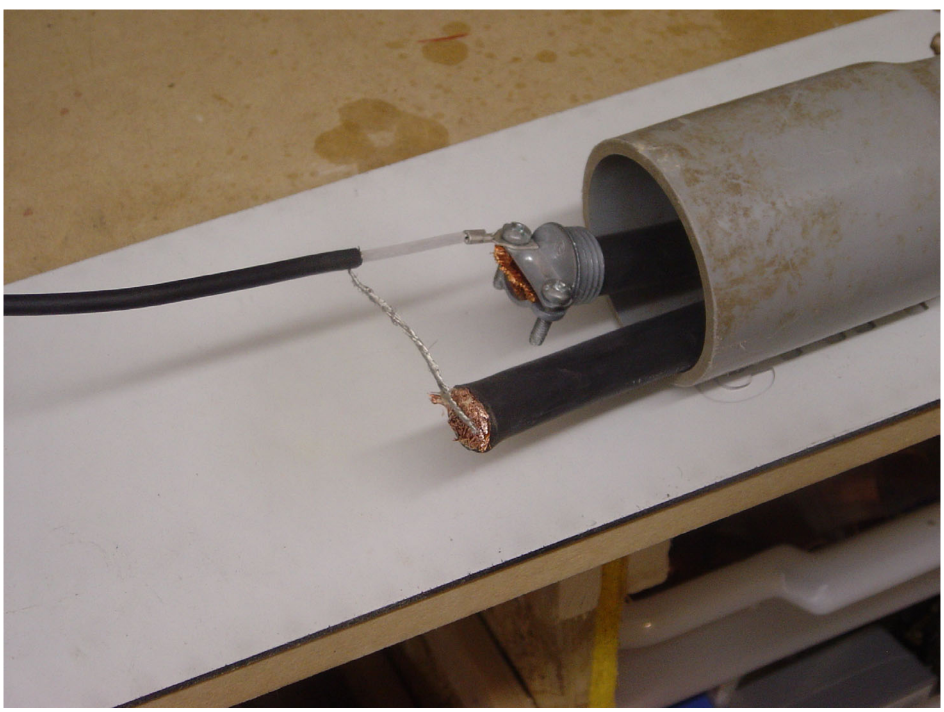

**Figure 6.1 Test Fixture Using Cable Clamp**

**'Grounded' Cable Test**

The trace shown in Figure 6.3 shows the results of testing the 3-foot long coaxial cable, shown in Figure 6.2, that is used to connect the jumper under test to the Tek 1503C. In this test the cable is grounded, the shield connects directly to the conductor, at the endpoint giving the characteristic inverted return pulse. The cable length shown is double the actual length because the signal propagates down and then back traveling twice the distance.

**Figure 6.2 Coaxial Cable For Connecting Jumpers to TDR.**

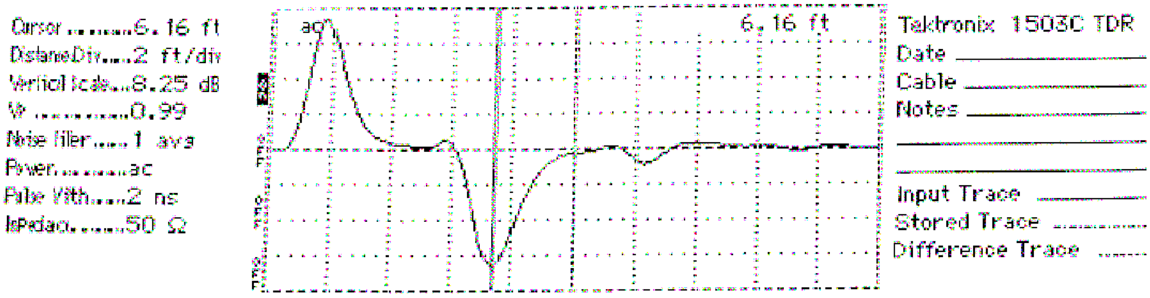


**Figure 6.3 TDR Trace of Connecting Coaxial Cable.**

**Testing Undamaged Jumpers**

Figure 6.4 shows the trace from testing a new and presumably undamaged, 10 foot long piece of 4/0 AWG stranded copper cable, often referred to as welding wire, in the test apparatus. Figure 6.5 shows the TDR and test setup.

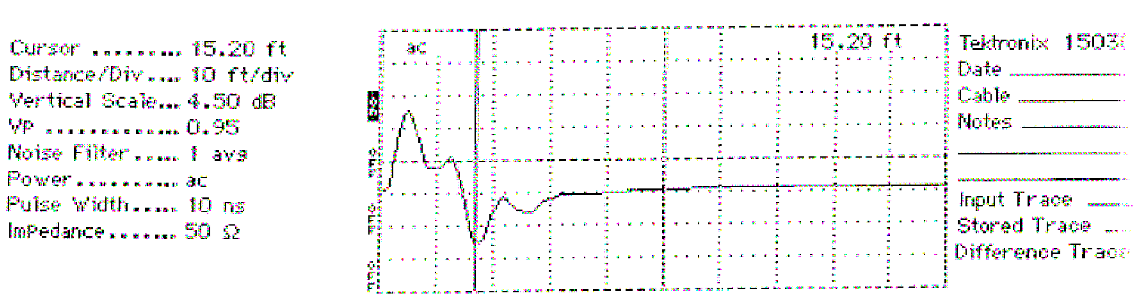


**Figure 6.4 TDR Trace from 10' Jumper**

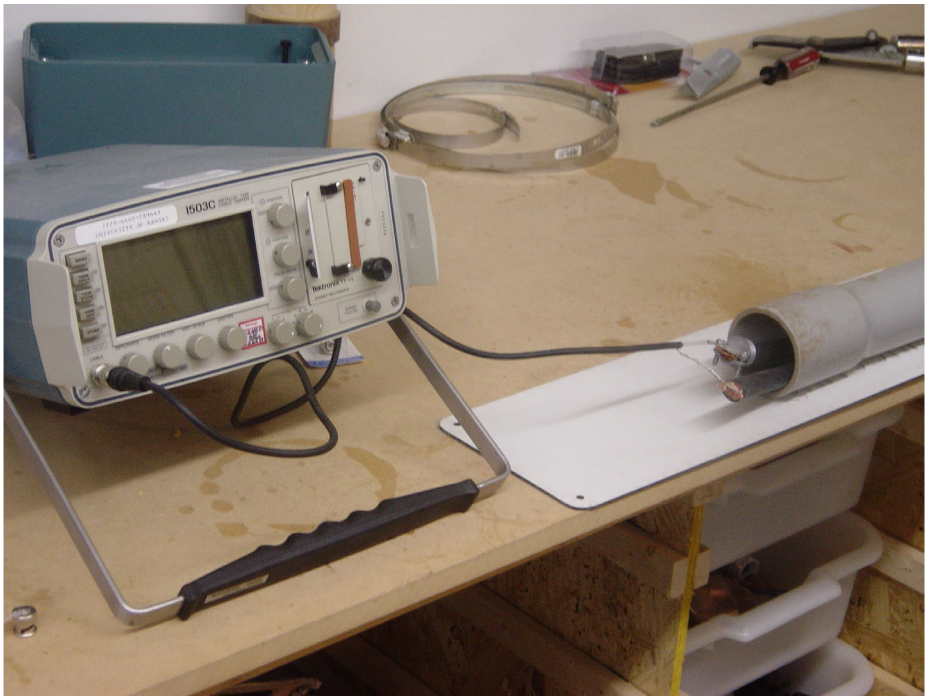

Figure 6.5 TDR Unit and Test Fixture.

**'Open' Cable Test**

The following trace, Figure 6.6, shows the reflections from the same 10 foot long cable only with an open end. The signal is reflected back in-phase with the initial pulse when it reaches the end of the cable.

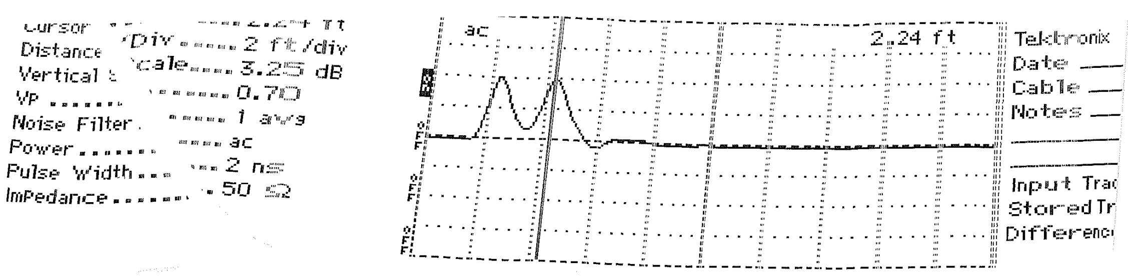


Figure 6.6 Trace of an Open Cable.

The previous experiments have shown the waveforms generated by shorting a cable and by opening a cable. The next experiments will examine the waveforms generated by a damaged cable. In this case the damage is of the form of cutting the cable while it's in its grounded configuration. What we would hope to see are reflections of increasing magnitude as the cable is severed more thoroughly, finally reaching the open trace condition. What was observed was that the jumper had to be so severely damaged before reflections occurred that the level of damage would easily be detected by even casual inspection of the cable. The traces in Figure 6.7 show the results when the cable was almost completely severed. In this state the damage would more easily be detected by visual inspection. The Tektronix 1503C uses a thermal printer to generate the traces shown in this document. The printer on this particular unit was in need of an overhaul and to that end some of these traces have less than the desired image quality.

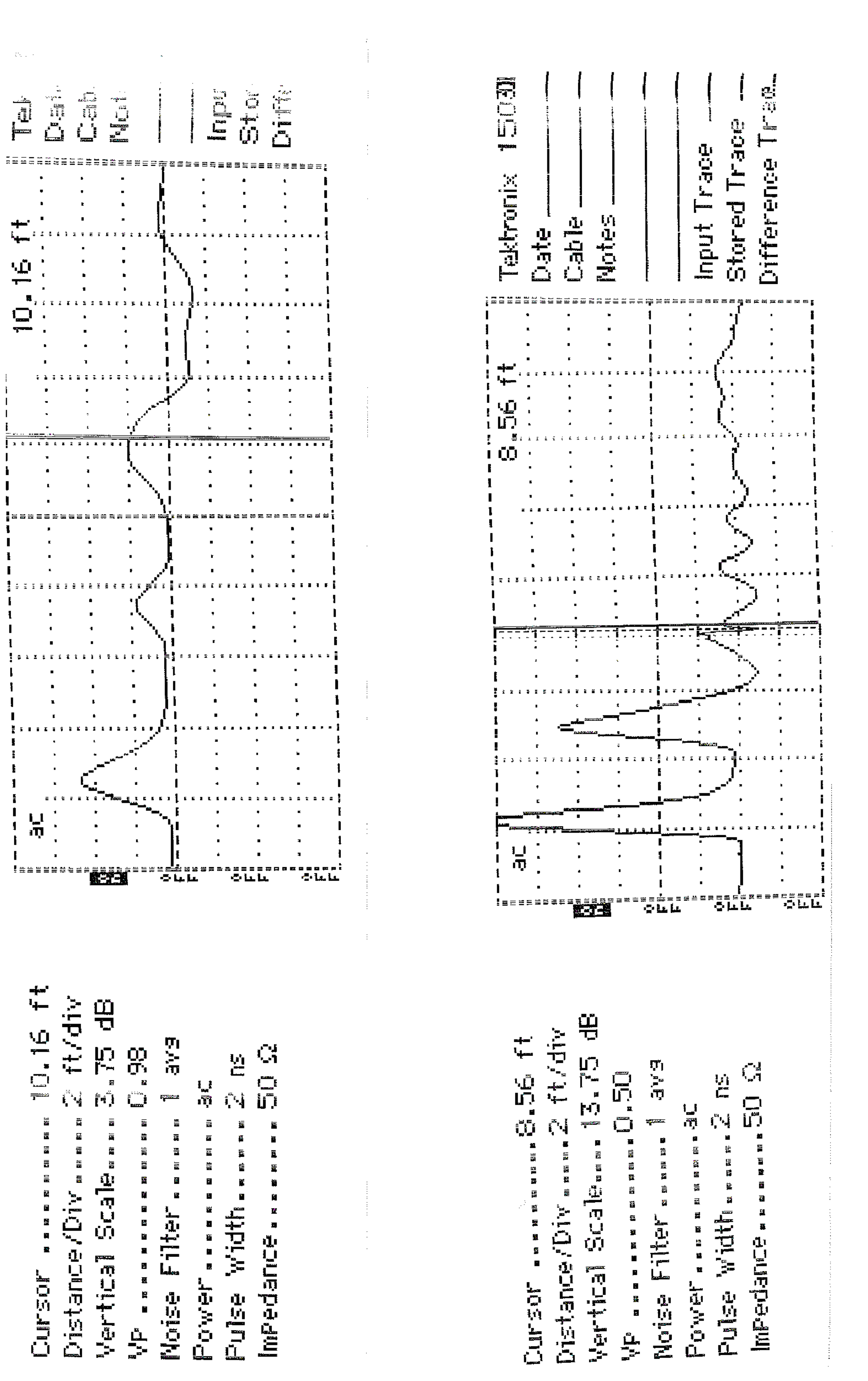


**Figure 6.7 TDR Traces From a 'Damaged' Jumper.**

*C h a p t e r 7*

# DATA ANALYSIS AND RECONCILIATION

The data collected and observations made are inconsistent with expectations. Experimental results on other types of cables with other types of TDR equipment suggest results as follows.

**Comparative Test Results**

Figure 7.1 shows a length of cable with a partial open approximately 2/3 of the way down the line.

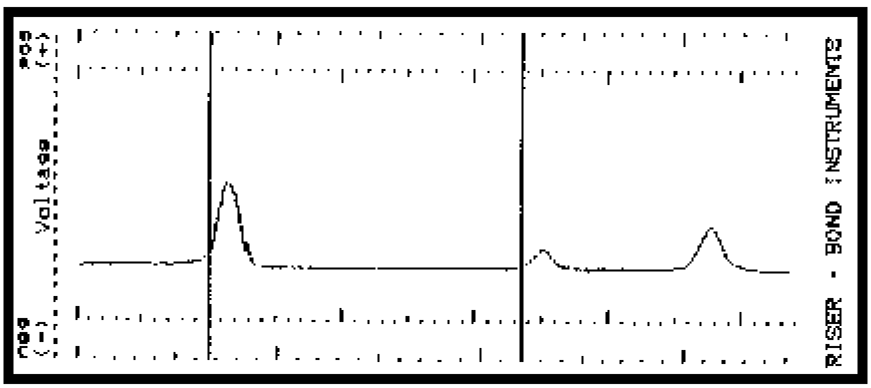


**Figure 7.1 Faulted Open Cable**

A partial open could easily be due to a damaged cable or incorrectly installed clamp assembly.

Figure 7.2 shows the expected results of a cable that has been joined at some point. This is the type of result we would expect to see where the jumper joins the ferrule of the clamp.

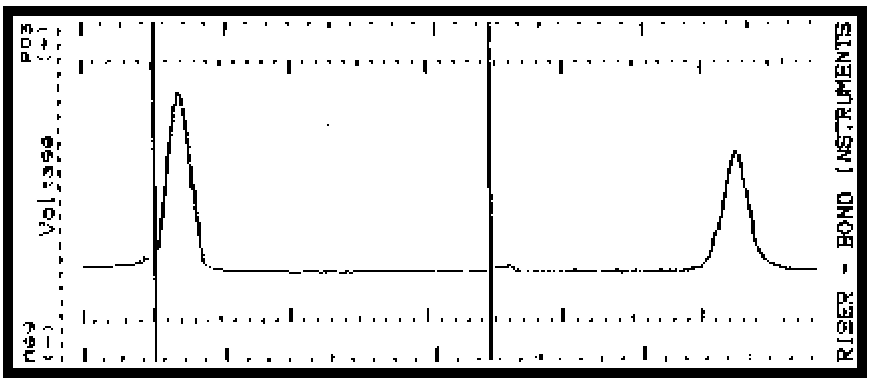


**Figure 7.2 TDR Response of Jointed Cable**

The amplitude of the second peak is directly proportional to the quality of the connection. This would directly relate to the instances when BPA had cables dismantle themselves under actual conditions of use.(Kolcio 2002) This area of higher impedance would generate tremendous heat and pressure causing the failure.

### Inconsistencies Explained

The inconsistencies between expected and actual results beg the question – why are they different? The initial testing shown in figures 6.4 and 6.6 demonstrate that the TDR is correctly detecting a cable with an open or shorted end. These two boundary conditions agree with the empirical data researched on multi-conductor cables. For example, telephone wire, shielded coaxial cables or other twisted pair cables. However practical experience shows that the failures detected in these multi-conductor cables are usually complete conductor breaks, hidden by the outer cable insulation, or termination problems with the connectors. In order for a reflection to occur, an impedance mismatch must occur. On a jumper cable of size 4/0, the loss of one or two or even a dozen strands has little impact on the impedance. While it's true in both cases that a loss of 50% of the conductors would result in a 50% increase in the impedance, the overall impedance of the large cable is much smaller than that of the small cable.

**Incomplete Testing**

The TDR isn't reporting damage to the cable because the TDR isn't testing the entire cable. TDR is equivalent to AC testing, actually 500 kHz in the case of the Tektronix 1503C. It is known that current density is non-linear in conductors based on the frequency of the current. This is known as the skin effect, $\delta$, and is approximated by:

$$\delta \equiv \sqrt{\frac{\rho}{\pi f \mu}} \qquad (11)$$

For copper conductors, $\rho = 6.787\text{x}10^{-7}$ $\Omega$-inches and $\mu = 3.192\text{x}10^{-8}$ weber/amp-inches. (Energy Automated Systems Unknown) Figure 7.3 depicts how AC current is distributed in a round conductor.(Energy Automated Systems Unknown)

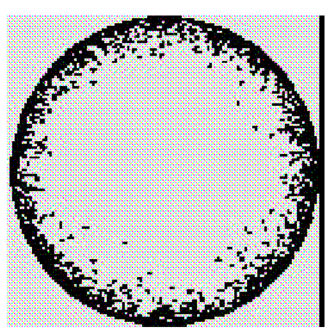

**Figure 7.3 Current Distribution Due to the Skin Effect in a Round Conductor**

A multi-stranded conductor closely approximates a solid conductor of the equivalent diameter for the basis of skin effect analysis. Some texts refer to a 'fill factor' that is used to approximate the air spaces between the strands. This fill factor affects, reduces, the overall conductivity of the cable. The theoretical value for the fill factor, $\eta$, is 0.9609 (Energy Automated Systems Unknown). However, since cables compress and strands don't remain perfectly round, the actual value of $\eta$ varies slightly. Using frequency, f, in Hertz, the resulting skin depth is calculated and shown in Table 7.1.

| Frequency | Skin Depth | | % |
|---|---|---|---|
| (Hz) | Inches | mils | Penetration |
| 1 | 2.601552215 | 2601.6 | 492.7% |
| 10 | 0.822683045 | 822.7 | 155.8% |
| 20 | 0.58172476 | 581.7 | 110.2% |
| 50 | 0.367915043 | 367.9 | 69.7% |
| 60 | 0.335858947 | 335.9 | 63.6% |
| 100 | 0.260155221 | 260.2 | 49.3% |
| 240 | 0.167929473 | 167.9 | 31.8% |
| 1000 | 0.082268305 | 82.3 | 15.6% |
| 500000 | 0.00367915 | 3.7 | 0.7% |

**Table 7.1 Skin Depth vs. Frequency for a Copper Conductor**

The % penetration is defined as the skin depth divided by the diameter of a 4/0 AWG conductor or 0.528 inches. (NFPA 2005) In other words it is a measure of how much of the cable is being used by the signal. At frequencies of 100 Hz and below the skin effect is negligible on a 4/0 AWG conductor as the penetration is approximately 50% or greater (50% from the edge of circle constitutes the entire area). At 500 kHz, where the TDR testing occurs, the skin depth is very small and all of the current is running along the edges. In fact each strand of a 4/0 AWG conductor is 106 mils in diameter, more than adequate to maintain a TDR pulse. Therefore it would seem that as each strand is cut the TDR pulse simply 'jumps' to another strand and continues about its business until the last strand is damaged.

*C h a p t e r 8*

# CONCLUSIONS

Testing of large power cables and cable assemblies in general continues to be a challenge. Simple Resistance Testing, TDR analysis and other methods all have associated challenges, benefits and consequences.

## Conclusions

Quantitatively, the experimental data suggest TDR equipment is inappropriate for testing grounding jumpers because of the high frequencies it is designed for. The lowest frequency setting on the Tektronix 1503C is 500 kHz while a frequency of 100 Hz or less is needed. The connectors on the equipment are also designed for small, high frequency connections. These connections require the use of an adapter that influences the results, which may introduce errors.

Qualitatively, the literature reviewed, particularly ASTM 2249 and the Bonneville Power Authority/Ontario Hydro Power study seem to indicate the low current, 10 A, testing is not a good predictor of whether or not a grounding jumper assembly will survive an actual fault. This suggests a research in a different direction. Anecdotal evidence states the jumpers that fail under an actual fault do so in a rather violent manner. BPA reports clamps 'blown off', insulation blistered and melted. In all cases these jumpers had overall resistances within the ranges suggested by ASTM and others.

## Recommended Additional Research

Additional research can be suggested in three main areas. The first of which is to determine whether or not a low frequency TDR can be constructed and used to get the same results seen on small, high frequency cables, on temporary grounding jumpers. A funding proposal to industry could provide impetus to develop this low frequency TDR. The second area to research is that of modeling a jumper under fault conditions. A fault may actually behave more like a lightning strike and have properties governed by high frequency analysis. Having a better understanding of how a fault affects a jumper could suggest alternative research. Finally, the third area, which may be a subset of the second, is to conduct forensic studies of cables that failed under fault conditions. Additional factors, moisture, oxidization, dirt, etc. may be discovered to have a significant impact on the jumpers' ability to survive a fault.

Assuming a definitive answer can be found, developing the solution into a portable, user-friendly appliance for the line worker will be critical to ensuring life safety when using grounding jumpers. In the end it falls upon the companies and personnel associated with the use of these jumpers to become knowledgeable and aware of the situations to which they're being exposed. No matter how useful and friendly the appliance is, if nobody uses it, it does no good.

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# *Appendix A*

TEKTRONIX 1503C SPECIFICATIONS

# Appendix A: Specifications

The tables in this chapter list the characteristics and features that apply to this instrument after it has had a warm-up period of at least five minutes.

The Performance Requirement column describes the limits of the Characteristic. Supplemental Information describes features and typical values or other helpful information.

## Electrical Characteristics

| Characteristic | Performance Requirement | Supplemental Information |
|---|---|---|
| Test Pulse<br>Width<br><br>Accuracy | <br>Selected: 2 ns, 10 ns, 100 ns, 1000 ns<br><br>2 ns ± 1 ns; 10 ns, 100 ns, 1000 ns ± 10% | <br>Measured at half sine amplitude point with matching termination. |
| Pulse Amplitude<br>Terminated<br><br>Unterminated | <br>−2.5 VDC ± 10% for 10 ns, 100 ns, 1000 ns; 2 ns ± 20%<br><br>−5.0 VDC ± 10% for 10 ns, 100 ns, 1000 ns | <br><br><br>Internal cable length prevents 2 ns pulse from reaching full unterminated voltage |
| Pulse Shape | 1/2 sine | |
| Pulse Output Impedance<br>Accuracy | Selected: 50 Ω, 75 Ω, 93 Ω, 125 Ω<br>1% | |
| Pulse Repetition Time | 350 μs nominal | |
| Vertical<br>Scale<br><br>Accuracy<br><br>Set Adjustment<br><br>Vertical Position | <br>0 dB to 63.75 dB gain<br><br>± 3%<br><br>Set incident pulse within ± 3%<br><br>Any waveform point moveable to center screen. | <br>256 values at 0.25 dB increments<br><br><br><br>Combined with vertical scale control. |
| Displayed Noise<br><br>Random<br><br><br><br>Aberrations | <br><br>≤ ± 1.0 division peak with 57 dB gain, filter set to 1<br>≤ ± 1.0 division peak with 63 dB gain, filter set to 8<br><br>≤ −30 dB p-p for 10 ns, 100 ns, 1000 ns test pulse<br>≤ −25 dB p-p for 2 ns test pulse | With matching terminator at panel. Beyond three test pulse widths after test pulse.<br><br><br><br><br>Within three test pulse widths after test pulse. dB is relative to test pulse. |

(continued next page)

| Characteristic | Performance Requirement | Supplemental Information |
|---|---|---|
| Cable Connection<br>Coupling<br><br>Max Input Susceptibility | <br>Capacitively coupled<br><br>± 400 V (DC + peak, AC at maximum frequency of 440 Hz). No damage with application for up to 30 seconds (might affect measurement capability). | |
| Distance Cursor Resolution | 1/25 of 1 major division | |
| Cursor Readout<br>Range<br><br>Resolution<br><br>Accuracy | <br>–2 ft to ≥ 50,000 ft (–0.61 m to 15,230 m)<br><br>0.04 ft<br><br>Within 2% ± 0.02 ft at 1 ft/div | <br>5 digit readout<br><br><br><br>Vp must be set within ± 0.5% of cable |
| Horizontal<br>Scale<br><br><br>Range | <br>1 ft/div to 5000 ft/div (0.25 m/div to 1000 m/div)<br>12 values: 1, 2, 5 sequence<br><br>0 to 50,000 ft (0 to 10,000 m) | |
| Horizontal Position | Any distance to full scale can be moved on screen | |
| Vp<br>Range<br><br>Resolution<br><br>Accuracy | <br>0.30 to 0.99<br><br>0.01<br><br>within ± 1% | <br>Propagation velocity relative to air |
| Custom Option Port | | Tek chart recorder is designed to operate with the 1503C. Produces a high resolution thermal dot matrix recording and waveform and control values. |
| Line Voltage | 115 VAC (90 to 132 VAC) 45 to 440 Hz<br>230 VAC (180 to 250 VAC) 45 to 440 Hz | Fused at 0.3 A<br>Fused at 0.15 A |
| Battery Pack<br>Operation<br><br>Full Charge Time<br><br>Overcharge Protection<br><br>Discharge Protection<br><br>Charge Capacity<br><br>Charge Indicator | <br>8 hours minimum, 30 chart recordings maximum<br><br>20 hours maximum<br><br>Charging discontinues once full charge is attained<br><br>Operation terminates prior to battery damage<br><br>3.4 Amp-hours typical<br><br>Bat/low will be indicated on LCD when capacity reaches approximately 10% | <br>+15° C to +25° C charge and discharge temperature, LCD backlight off. Operation of instrument with backlight on or at temperatures below +10° C will degrade battery operation specification |

## Environmental Characteristics

| Characteristic | Performance Requirement | Supplemental Information |
|---|---|---|
| Temperature | | |
| Operating | −10° C to +55° C | Battery capacity reduced at other than +15°C to +25°C |
| Non-operating | −62° C to +85° C | With battery removed. Storage temp with battery in is −20° C to +55° C. Contents on non-volatile memory (stored waveform) might be lost at temps below −40° C. |
| Humidity | to 100% | |
| Altitude | | MIL−T−28800C, Class 3 |
| Operating | to 10,000 ft | |
| Non-operating | to 40,000 ft | |
| Vibration | 5 to 15 Hz, 0.06 inch p−p<br>15 to 25 Hz, 0.04 inch p−p<br>25 to 55 Hz, 0.013 inch p−p | MIL−T−28800C, Class 3 |
| Shock, Mechanical | | |
| Pulse | 30 g, 11 ms 1/2 sine wave, total of 18 shocks | MIL−T−28800C, Class 3 |
| Bench Handling | | MIL−STD−810, Method 516, Procedure V |
| Operating | 4 drops each face at 4 inches or 45 degrees with opposite edge as pivot | Cabinet on, front cover off |
| Non-operating | 4 drops each face at 4 inches or 45 degrees with opposite edge as pivot. Satisfactory operation after drops. | Cabinet off, front cover off |
| Loose Cargo Bounce | 1 inch double-amplitude orbital path at 5 Hz, 6 faces | MIL−STD−810, Method 514, Procedure XI, Part 2 |
| Water Resistance | | MIL−T−28800C, Style A |
| Operating | Splash-proof and drip-proof | Front cover off |
| Non-operating | Watertight with 3 feet of water above top of case | Front cover on |
| Salt Atmosphere | Withstand 48 hours, 20% solution without corrosion | |
| Sand and Dust | Operates after test with cover on, non-operating | MIL−STD−810, Method 510, Procedure I |
| Washability | Capable of being washed | |
| Fungus Inert | Materials are fungus inert | |

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